Evaluation of the "0.1% Rule" for Docking Maneuvers

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Abstract

SIMULATED docking maneuvers were performed to assess the effect of initial velocity on docking failure rate, mission duration, and Δv (fuel consumption). Subjects performed simulated docking maneuvers of an orbital maneuvering vehicle with initial velocities of 0.3, 3.0, 5.0, 7.0, and 9.0 m/s to a space station. The effect of the removal of the range and rate displays (simulating a ranging instrumentation failure) was also examined. Naive subjects were capable of achieving a high success rate in performing simulated docking maneuvers without extensive experience. Failure rate did not significantly increase with increased velocity. The amount of time subjects reserved for final approach increased with starting velocity. Piloting of docking maneuvers was not significantly affected in any way by the removal of range and rate displays. The "0.1% rule" is seen to be overly conservative for nominal docking missions.

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Introduction

The relative motion of orbital maneuvering vehicles (OMV's) with respect to a space station is very difficult to visualize because of nonlinearities in the governing equations of motion. Simulation experiments are necessary to better understand pilot response to these nonintuitive phenomena.

Current Shuttle rendezvous guidelines are very conservative suggesting that a "0.1% rule" be followed. This rule dictates that the Shuttle's relative closing velocity with respect to the space station should be maintained at a value that is 0.1% of its range per second. For example, at a range of 1000 ft, the velocity should be 1 ft/s. After 100 s, the Shuttle arrives at a range of 900 ft and the range rate is decreased to 0.9 ft/s.[6] A docking from an initial range of 1 km would take about 1 h to complete if this guideline were followed. This is an arbitrary rule of thumb designed to afford the pilot a sufficient safety margin with which to successfully perform the maneuver.

One area in which data suggest the need for further evaluation of current docking guidelines is workload. Workload has been under intensive scrutiny in the airline industry for some time. Here, crew inactivity may be caused by cockpit automation. Related concerns include the potential for automation to reduce crew alertness or cause them to be easily distracted.[8] Certain recent airline accidents are interpreted to have been automation induced and they may be preventable in the future by putting the human "into a more active role in the control loop."[9] Pilot-astronauts and spacecraft are analogous to airline pilots and aircraft and this workload level concern is relevant to space operations as well. Research has shown that tasks containing relatively long periods of inactivity are perceived as being high in workload.[1] Both too many and too few inputs required per unit time are potentially hazardous. Minimizing workload is not necessarily the safest approach.

Experimental Methods and Apparatus

This experiment was conducted in the space station proximity operations simulator at NASA Ames Research Center. The simulator primarily consists of one three-degree-of-freedom hand controller and three "windows" on which the computer-generated imagery is presented. Buttons on the hand controller are used to select the thruster acceleration values for each axis among choices of 0.01, 0.1, and 1.0 m/s. Detailed descriptions of the simulator are available elsewhere.[3-5]

Test subjects were required to "fly" 10 remote docking maneuvers of an OMV to a space station in a 270 n.mi. orbit beginning from an initial range of 304.8 m (1000 ft) on the −V-bar (along the velocity vector in the minus direction). A repeated measures design was used with five initial velocities: 0.3, 3.0, 5.0, 7.0, and 9.0 m/s. From this direction, orbital mechanics effects cause the vehicle to rise and the subjects were instructed to counteract this tendency to accomplish a successful docking. The order that these velocities were presented was randomized and was different for each subject. Subjects were requested to resist boredom at the slowest velocity and were prohibited from accelerating to decrease the mission duration. In addition, each subject also performed 10 attempts without the benefit of operational range and rate displays. These trials were performed last (at an initial velocity of 3.0 m/s).

Each subject was issued a training manual for perusal prior to experimentation. Training consisted of performing 10 successful dockings with an initial velocity of 3.0 m/s. Once 10 successful dockings were achieved, training was considered complete and data collection began.

Certain range and rate conditions had to be satisfied for a docking attempt to be considered successful. These conditions included the following: forward range of 2.0 m with an approach velocity no greater than 0.15 m/s, and up/down and left/right ranges and rates with absolute values that did not exceed 0.23 m and 0.06 m/s, respectively. These values were derived from the proceedings of a NASA workshop on rendezvous and docking and were believed to be the most recent.[7]

Results

Eight male subjects were tested for approximately 6 h each. (Time considerations prevented some of the subjects from completing all 10 of the runs at 0.3 m/s but no subject performed fewer than 8.) Although most of the unsuccessful missions were not tragic in nature, for experimental purposes, "unsuccessful" was operationally defined as not satisfying the terminal range and rate conditions mentioned previously. The average failure rate by subject or initial condition was 13.2%. A two-way analysis of variance (ANOVA) was performed on these data with subject and initial condition (velocity) as factors. Only the between subject data were significant, with an F ratio of $F(7,35) = 3.38$ ($p = 0.007$).

Since mission duration and total impulse are heavily influenced by the initial velocity of the vehicle, the data for

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those parameters are more important for mission operations considerations than for human-performance analyses. Consequently, mission duration and total impulse were "normalized" by subtracting out appropriate reference values. The reference value for mission duration was computed by dividing the initial range by the initial velocity. This provided a theoretical minimum time for a linear, one-dimensional system (which does not characterize the orbital environment) with impulsive start and stop. The parameter thus obtained was termed "reserve time," as this was the time the subject reserved for himself in order to dock successfully.

In a similar fashion, the starting impulse and the impulses used to decelerate the vehicle were subtracted from the total impulse to arrive at the value used to maintain the OMV on or near the V-bar. (Since the OMV rarely came to a full stop upon docking, the vehicle was assumed to have a residual velocity of 0.1 m/s for this calculation.) This derived parameter was called "radial impulse" as this was the sum of the radial impulses used to achieve a successful docking.

Reserve time medians averaged over all subjects ranged from a low of -22.2 s at 0.3 m/s to a high of 108.4 s with the no-display trials. (Whenever the altitude of the OMV is below that of the station, it has a lower orbital period and the range decreases. A negative reserve time is achieved by reducing the altitude for the OMV for so long that this difference in period significantly reduces the duration of the docking maneuver.) Across treatments, the averages ranged from 23.8–114 s. For the reserve time medians, the omnibus F test produced ratios of $F(5,35)=6.73$ ($p<0.001$) and $F(7,35)=2.23$ ($p=0.055$) for the between treatment and between subject data, respectively.

The F ratios for radial impulse medians were $F(5,35)=2.81$ ($p=0.031$) and $F(7,35)=6.68$ ($p<0.001$) for between treatment and between subject analyses. Averages of medians across subjects ranged from 1.02 m/s at 0.3 m/s to 1.77 m/s at 9.0 m/s. Across treatments, the values were 0.75 m/s for subject 3 to 2.1 m/s for subject 5 with an average of 1.26 m/s.

Two-way ANOVAs were also conducted for the three parameters using only the 3.0 m/s and no-display (also 3.0 m/s) medians to determine the effect of the removal of the displays. None of these F ratios proved significant.

Discussion—Analysis

Before discussing the results in any detail, it must be emphasized that none of the subjects had any background or experience with orbital mechanics effects or any high-performance jet flight training. The data show how well naive subjects can do without either of the aforementioned advantages. Also, none of the pilots had access to any orbital trajectory-planning device to assist them with their docking missions. It is expected that NASA pilots with the preceding qualifications, and more, could easily surpass the best mission duration, fuel consumption, and success rate values achieved here. Subjects and NASA pilots alike can be trained to virtually any desired design point for any, or all, of the three parameters before they are considered competent to perform an actual docking.

Subjects had different risk profiles; some were risk prone and some were risk averse. In actuality, docking velocities would not be chosen because of their associated success rate in simulations. Rather, the user population of pilots would be chosen from their established success rate in simulated maneuvers. Unlike other vehicles such as aircraft or automobiles where the landing scheme or speed limit must be designed to safely accommodate the worst pilots (drivers), for spacecraft and space missions, "the simulator defines the user population rather than vice versa." A velocity would not be selected because it induced the lowest failure rate averaged over all subjects, rather, those who peformed the best in the simulated mission would be chosen to perform the actual mission.[2]

While mission duration varied inversely with initial velocity, reserve time increased monotonically with initial velocity with the no-display runs performed at 3.0 m/s requiring more reserve time than the runs at 9.0 m/s. This effect is mostly due to the equations of motion governing orbital flight. By traveling at a different altitude from the station, forward velocity was obtained without the use of fuel. During the longer (slower) missions, orbital mechanics effects had more time to work to the subjects' advantage and thus reduce reserve time.

The radial impulse data were significant both when analyzed by subject and by treatment. This indicates that not only are different amounts of fuel required to compensate for a nonlinear environment dependent upon the initial velocity, but that some subjects are significantly more fuel efficient when it comes to applying these radial burns.

The fact that removal of the range and rate display at 3.0 m/s did not significantly affect the data for any of the parameters is very important. This indicates that such displays, while probably psychologically comforting, are redundant in a real-life situation, when combined with the visual image of the approaching vehicle, and are unnecessary for nominal dockings. They did not help the test subjects perform more rapid, more fuel efficient, or safer dockings. They would most likely be more useful in anomalous situations.

Conclusions

1) The amount of time pilots reserved for final approach increased with starting velocity. The slow forward velocities allowed more time for the orbital mechanics effects to play a role and were thus used to the pilot's advantage in gaining forward velocity for free.

2) Remote piloting of docking maneuvers was not significantly affected in any way by the removal of range and rate displays.

3) The initial condition significantly affected the subjects' use of reserve time and radial impulse.

4) The "0.1% rule" for docking is overly conservative from a human performance point of view.

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